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16. ABSTRACT

We studied the effects of 2-h exposure to ozone in 14 nonsmoking males under four environmental conditions. Thirty minutes of exercise at 40% Vo_{2max} was performed from 60 to 90 min for group A and 30 to 60 min for group B. Pulmonary function changes, determined throughout exposure, were greatest immediately after exercise in both groups. Few changes occurred before the exercise period. We cnclude that the effects of ozone are most severe immediately after exercise and that heat stress may modify the overall effect of ozone on pulmonary function.

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Influence of exercise and heat stress on pulmonary function during ozone exposure

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FOLINSBEE, L. J., S. M. HORVATH, P. B. RAVEN, J. F. BEDI, A. R. MORTON, B. L. DRINKWATER, N. W. BOLDUAN, AND J. A. GLINER. *Influence of exercise and heat stress on pulmonary function during ozone exposure.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 43(3): 409-413, 1977.—We studied the effects of a 2-h exposure to ozone (0.5 ppm) in 14 nonsmoking males under four environmental conditions (WBGT (wet bulb–globe temperature index) = 64.4, 80.0, 85.2, and 92.0°F). The subjects were divided into two groups, *A* (n = 8) and *B* (n = 6). Thirty minutes of exercise at 40% $\dot{V}O_{2\ max}$ was performed from 60 to 90 min for *group A* and 30 to 60 min for *group B*. Pulmonary function changes, determined throughout exposure, were greatest immediately after exercise in both groups. Few changes occurred before the exercise period. However, the decrease in FVC (826 ml) and $FEV_{1.0}$ (937 ml) following exercise was more than twice as large as the decrement seen at end exposure (388 and 423 ml, respectively). Measures of maximum expiratory flow (FEF 25-75%, FEF 50%, FEF 75%) showed similar reductions. In many cases, reversal of these changes occurred during the remainder of the exposure period. The greatest decrease in FVC occurred when heat and ozone exposures were combined (WBGT = 92.0°F). We conclude that the effects of ozone are most severe immediately after exercise and that heat stress may modify the overall effect of ozone on pulmonary function.

temperature; humidity; pulmonary function; oxidant air pollution

EXPOSURE OF THE LUNG to ozone at concentrations known to exist in the urban atmosphere (21) causes irritation and discomfort as well as impairment of pulmonary function. These effects are apparently related to the volume of ozone breathed per unit time (10, 20). The method used in many studies to increase ventilation, and thus volume of ozone inspired, has been to perform submaximal exercise. This method of increasing the minute ventilation not only increases volume but also depth of inspiration (tidal volume), inspiratory flow rate, and possibly changes the orifice of entry (mouth vs. nose). Kagawa and Toyama (16) examined the effects of a high concentration of ozone (0.9 ppm) during a 5-min exercise period and noted a marked decrease in specific airway conductance. Other investigators (3, 8, 13, 20) have noted the different effects of resting as compared to exercising exposures but they have not examined the immediate effect of the exercise period. Lack of improvement in performance of high school runners has also been linked statistically with ambient ozone concentrations (22). In this investigation we have examined the pulmonary function changes during ozone exposure before, immediately after, and for up to 1 h following a bout of submaximal exercise.

Many experimental ozone exposures (3, 8, 13, 17, 20) have been performed under standard room temperature conditions (20–25°C, 45-50% rh) although oxidant pollutant episodes are known to occur primarily during periods of air stagnation which are accompanied by high ambient temperatures. Higher temperatures were used in one series of exposures (11, 12), but the effect of heat and humidity on pulmonary function responses to ozone exposure has not been studied. Therefore, we have also examined the influence of hot and humid conditions, in combination with ozone exposure, on the pulmonary function of young male nonsmokers.

METHODS

Fourteen healthy nonsmoking males, aged 20-25 yr, were selected from some 30 volunteers from the university population.[1] Preliminary screening tests included a medical history, a resting 12-lead electrocardiogram and a battery of clinical spirometric tests. Subsequently, the subjects performed a maximal aerobic capacity test on a treadmill. Physical and physiological data of these subjects are summarized in Table 1. The subjects were divided into two groups, *A* (n = 8) and *B* (n = 6).

Experimental design. The subjects were exposed to each of four environmental conditions twice, once with filtered air and once with 0.50 ppm ozone (range 0.44-0.57 ppm). Exposures were separated by a minimum of 1 wk and were performed at the same time of day. The four environmental conditions were: *1*) 25°C, 45% rh; *2*) 31°C, 85% rh; *3*) 35°C, 40% rh; *4*) 40°C, 50% rh. (Wet bulb–globe temperature (WBGT) equivalents are 64.4, 85.2, 80.0, and 92.0°F, respectively.) The filtered air exposures with environmental conditions *1–4* are referred to as codes 1–4; the ozone exposures are referred to as codes 5–8 respectively.

Prior to exposure, the subjects were trained in the

[1] The nature and purpose of the study and the risks involved were explained verbally and given on a written form to each subject prior to their voluntary consent to participate. The protocol and procedures for this study have been approved by the Committee on Activities Involving Human Subjects, of the University of California, Santa Barbara.

TABLE 1. *Subject data*

	Ht, cm	Wt, kg	Age, yr	FVC, ml BTPS	$FEV_{1.0}$, ml BTPS	$\dot{V}O_{2\ max}$, l/min BTPD
Group A ($n = 8$)	181.5 (178–191)	76.1 (63–90)	21.4 (20–25)	6,165 (5,005–8,304)	4,936 (4,070–6,615)	3.78 (2.97–4.39)
Group B ($n = 6$)	181 (172–191)	74.6 (64–85)	20.2 (20–21)	5,737 (4,690–6,604)	4,637 (4,145–5,056)	3.96 (3.33–4.38)

Values are means with ranges given in parentheses.

performance of pulmonary function tests which included forced vital capacity (FVC), maximum voluntary ventilation (MVV), functional residual capacity (FRC), airway resistance (Raw), and associated calculated parameters. A clinical chest examination was also performed. These procedures were repeated following the exposure.

During the exposure, *group A* subjects rested in the sitting position for 1 h, exercised for 30 min on a treadmill at approximately 40% of $\dot{V}O_{2\ max}$ (mean O_2 uptake = 1.50 l/min), and then were seated for a further 30 min. *Group B* underwent a similar exposure but exercised in the second 0.5 h, and rested for the final hour of exposure. The 2-h exposure was divided into eight 15-min periods. Forced vital capacity (best of two trials) was measured in periods 1, 2, 4, 7, and 8 for *group A* and periods 1, 2, 5, 6, and 8 for *group B*. Ventilation and heart rate were monitored intermittently during the exposure periods.

Pulmonary function tests were performed in the standing position. A 13.5-liter Benedict-Roth spirometer or a wedge spirometer was used for the determination of lung volumes (VC, IC, ERV, FRC), forced expiratory parameters (FVC, $FEV_{1.0, 2.0, 3.0}$, FEF 50%, FEF 75%, FEF 25-75%), and MVV (abbreviations according to (1)). FRC was determined using a helium-dilution technique. Thoracic gas volume and airway resistance (Raw) were measured in a body plethysmograph using the method of DuBois et al. (6, 7). All values were corrected to BTPS.

A Benedict-Roth-type spirometer was used for pre- and postexposure measurements and a wedge spirometer was used for in-chamber measurements. There was a small systematic difference (2.35% lower values for wedge) between the two spirometers. Observations were not corrected for this difference since no direct comparisons were made between data obtained on the two instruments.

A double-walled acrylic chamber measuring 1.8 m x 2.4 m x 2.6 m high was used for exposures. A dehumidifier and steam port were used to maintain relative humidity at the desired level and an electric heater and air conditioner were used to maintain chamber air temperature. Inlet air was dried (silica gel) and filtered through activated charcoal and particulate filters at a rate of 500 l/min (turnover time approximately 22 min). Ozone was generated from oxygen with an ultraviolet ozone generator and added to the chamber air supply. Ozone concentration was monitored continuously with a chemiluminescent ozone analyzer (McMillan). The ozone concentration was checked periodically by the neutral-buffered potassium iodide method (19).

Data were analyzed by a three-factor analysis of variance with repeated measures across treatment conditions and time. Treatment conditions were *a*, filtered air or ozone, and *b*, the four combinations of temperature and humidity. Levels of factor *c* were either pre- and posttest measurements or intervals within the exposure period. Such a design permits not only observations of the effects of the main factors but also of interaction between factors. For example, an AC interaction would indicate differences in pre- and posttest response due to breathing either ozone or filtered air regardless of the environment. When interaction effects were significant, a test for simple main effects was applied, followed by the Newman-Keuls test of ordered means where appropriate.

RESULTS

A portion of these data (*group A*) has appeared in a previous technical report (15).

Pulmonary function. The changes in pulmonary function which occur following exposure are summarized in Table 2. Following ozone exposure vital capacity decreased an average of 350 ml in *group A* and 388 ml in *group B* ($P < 0.05$). The decrease in vital capacity was accompanied by a decrease in inspiratory capacity which averaged 300 and 254 ml, respectively, for *groups A* and *B*. There were no significant alterations in ERV, FRC, or RV as a result of ozone exposure. However, total lung capacity was reduced 250 ml in *group A* and 213 ml in *group B*. In both groups the RV/TLC ratio tended to increase ($P < 0.10$).

TABLE 2. *Pulmonary function changes following exposure to filtered air or 0.50 ppm ozone*

		Group A		*Group B*	
		Pre	Post	Pre	Post
VC	FA	6,223	6,206	5,628	5,604
	O_3	6,241	5,895*	5,689	5,301*
$FEV_{1.0}$	FA	5,035	4,943	4,607	4,596
	O_3	5,098	4,581*	4,666	4,246*
$FEV_{3.0}$	FA	6,078	6,057	5,518	5,483
	O_3	6,075	5,721*	5,539	5,177*
IC	FA	3,927	3,899	3,537	3,619
	O_3	4,010	3,702*	3,596	3,343*
ERV	FA	2,286	2,318	2,073	1,959
	O_3	2,233	2,197	2,092	1,960
FRC	FA	4,029	4,189	3,694	3,708
	O_3	4,175	4,234	3,728	3,770
RV	FA	1,731	1,870	1,621	1,748
	O_3	1,942	2,038	1,635	1,810
TLC	FA	7,954	8,075	7,249	7,352
	O_3	8,182	7,933	7,324	7,111*
FEF 25-75%	FA	5.28	5.20	5.52	5.62
	O_3	5.30	4.61*	5.50	4.99†
MVV	FA	214.2	206.5	186.7	185.7
	O_3	222.6	206.6	187.7	167.7*
FEF 50%	FA	5.67	5.52	5.98	5.75
	O_3	5.79	4.95*	5.84	5.31
FEF 25%	FA	2.71	2.47	3.21	3.13
	O_3	2.51	2.34	2.94	2.57
Raw	FA	1.81	1.97	1.61	1.79
	O_3	1.89	2.29	1.75	2.03

See text for explanation of *group A* and *B* protocols. * Postexposure in ozone significantly less than preexposure or postexposure in filtered air ($P < 0.05$). † Postexposure in ozone significantly less than preexposure or postexposure in filtered air ($P < 0.10$).

Flow-related pulmonary function measurements indicated a reduction in maximum expiratory flow following ozone exposure. The reduction in $FEV_{1.0}$ was larger than the drop in vital capacity and averaged 500 ml (*A*) and 423 ml (*B*) in the two groups. The decline in $FEV_{3.0}$ was of the same magnitude as the drop in vital capacity. FEF 25-75% fell by 0.7 l/s (*A*) and 0.5 l/s (*B*), respectively. Although FEF 50% and FEF 75% decreased following ozone exposure, the variability in these measures was large and the decreases were only significant for FEF 50% in *group A*. MVV was reduced following each exposure, but further reduction due to ozone exposures was only seen in *group B*. Airway resistance increased following exposure to both filtered air and ozone.

The changes in expiratory flow and lung volumes during the exposure are summarized in Fig. 1. Preceding the exercise period, there were minimal alterations in pulmonary function. In both *groups A* and *B*, the greatest reduction in all pulmonary function parameters occurred following the exercise period. This effect is seen more dramatically with *group B* than *group A*. Postexercise FVC was reduced by 826 ml, more than twice the decrease (388 ml) seen at end exposure. Similarly, $FEV_{1.0}$ fell an average of 937 ml after exercise but was only decreased 523 ml at end exposure. The decrease in FVC, $FEV_{1.0}$, FEF 25-75% and FEF 75% was greatest at the end of the exercise period ($P < 0.01$) and thereafter tended to return toward the preexposure value despite continued exposure to ozone.

There was a trend toward a greater impairment of pulmonary function when ozone and heat exposure were combined. For *group A*, the reduction in vital capacity was significant in codes 4 and 8, the most extreme heat exposure in filtered air and ozone, respectively. In *group B*, the greatest reduction in MVV occurred following the code 8 (ozone plus heat) exposure. Ventilation (BTPS) during exercise was higher in codes 4 and 8 (39.7 l/min) than in all other exposure conditions (35.2 l/min).

We pooled the data ($n = 14$) for pre- and postexposure measurements for the two groups; statistical analysis showed essentially the same changes as in the individual groups. These data are summarized in Table 3. Both vital capacity and maximum expiratory flow were reduced with ozone exposure. There was a trend for a greater reduction when heat stress and ozone exposure were combined, but this effect was only significant for the vital capacity measurements. FEF 50% and FEF 75% did not show a significant change with ozone exposure in the postexposure measurement.

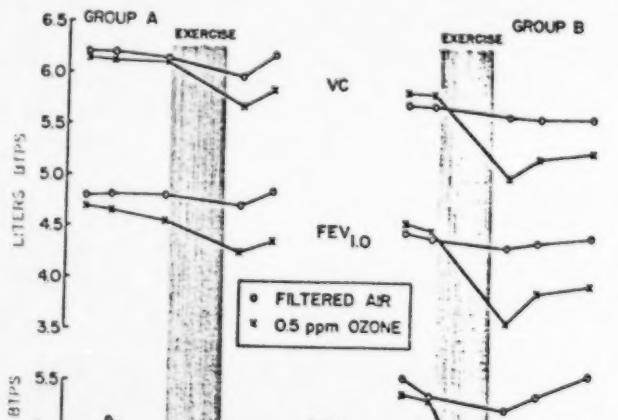

FIG. 1. Change in vital capacity (VC), forced expired volume in 1 s ($FEV_{1.0}$) and maximal midexpiratory flow (FEF 25-75%) during exposure to filtered air or ozone (0.5 ppm) for 2 h. Exercise at 45% $VO_{2\,max}$ was performed between 60 and 90 min for *group A* and between 30 and 60 min for *group B*. Filtered air exposures include overall means from codes 1–4; ozone exposures include overall means from codes 5–8.

DISCUSSION

The presence of ozone in the chamber air had a marked effect on pulmonary function, resulting in reduction of vital capacity, primarily as a result of a decreased inspiratory capacity, as well as a decline in maximum expiratory flow throughout the full range of vital capacity. Such changes have been observed previously with exposure of human subjects to similar concentrations of ozone (3, 11–13, 17, 20). The decline in vital capacity could result from a decreased maximum inspiration or an increase of residual volume. Although a decreased inspiratory capacity could result from an increase in end-expiratory lung volume, the lack of change in FRC confirms that the decreased IC results from a decreased maximum inspiration and thus a decline in TLC. This observation is consistent with the findings of Clamann and Bancroft (5) and Silverman et al. (20). On the other hand, Hazucha and associates (13) found no significant change in TLC but did find a rise in residual volume which contributed to the decrease in vital capacity. Many factors related to the experimental design such as amount of exercise, ozone concentration, temperature and humidity of the exposure chamber, and time period between the termination of exposure

TABLE 3. *Changes in pulmonary function following exposure to either filtered air or 0.50 ppm ozone: combined data for groups A and B ($n = 14$)*

	Code	Filtered Air				0.50 ppm Ozone			
		1	2	3	4	5	6	7	8
VC, ml	Pre	5,914	5,888	5,975	5,842	5,946	5,899	5,964	5,937
	Post	5,931	5,904	5,923*	5,715*	5,715††	5,566††	5,574††	5,408††
$FEV_{1.0}$, ml	Pre	4,701	4,883	4,961	4,821	4,895	4,774	4,789	4,565
	Post	4,679	4,872	4,767	4,638	4,512††	4,405††	4,301††	4,241††
$FEV_{3.0}$, ml	Pre	5,524	5,911	5,842	5,772	5,807	5,768	5,753	5,793
	Post	5,536	5,814	5,782	5,679	5,544††	5,459††	5,409††	5,274††
MMEF, l/s	Pre	5.29	5.53	5.26	5.34	5.40	5.29	5.14	5.26
	Post	5.10	5.44	5.27	5.56	4.76††	4.73††	4.57††	4.64††
MEF 50%, l/s	Pre	5.55	5.48	5.90	6.11	5.95	5.71	5.36	5.75
	Post	5.55	5.37*	5.55*	5.62*	5.26††	4.98††	4.68††	5.07††
MEF 25%, l/s	Pre	3.06	2.80	2.86	2.95	2.77	2.58	2.41	2.93
	Post	2.73	2.70	2.69	2.78	2.31	2.53	2.26	2.51

* Posttest values are lower than pretest ($P < 0.05$). † Posttest values after 0.50 ppm ozone exposure are lower than those after filtered air ($P < 0.05$).

and the postexposure tests could contribute to the variation in results seen in these different investigations. The chest discomfort experienced by the subjects and the difficulty in taking a deep breath suggest that the decreased maximum inspiration may result from either a voluntary or reflex reduction of inspiratory effort. Stimulation of irritant receptors (3, 8, 20) or altered sensitivity of lung inflation receptors (14) could cause discomfort on inspiration. Although we made every attempt to ensure a maximum effort on the part of our subjects, it is not clear whether the limitation to inspiration could be overcome in exceptionally well motivated subjects.

The changes in maximum expiratory flow are similar to those found in other studies (3, 11–13, 20). The decline in maximum expiratory flow results partly from a decline in TLC. Consequently the subject was forced to perform the maximum expiratory maneuver over the lower 80-90% of the flow-volume curve and $FEV_{1.0}$, FEF 25-75%, and FEF 50% are reduced. Using the mean data of Bass (2) a 14% reduction in TLC would result in a 17% drop in FEF 50%. However, the measures of maximum expiratory flow dropped some 25% following the exercise period in ozone (*group B*) which suggested that some degree of bronchoconstriction occurred. The almost 30% reduction in FEF 75% (postexercise) when only a 12% reduction could be accounted for by the 14% reduction in TLC lends further support to this argument. A decline in $FEV_{1.0}$ and FEF 25-75% may be partially attributed to an increase in large and small airways resistance which probably occurred as a result of reflex bronchoconstriction secondary to stimulation of tracheobronchial irritant receptors. The decline in $FEV_{1.0}$ (7.9% for pooled data code 5) is of the same order of magnitude (8.4%) that would be expected when an effective dose is calculated using the formula of Silverman et al. (20) (i.e., in this study, the effective dose = 1.5 rest dose). Retrospective questioning of the subjects revealed that the respiratory symptoms disappeared within 3–4 h.

It is significant that the greatest change in pulmonary function during ozone exposures occurred immediately following the exercise period. The protocol was changed to include *group B* so that observations could be made during a longer postexercise recovery period. The results from another study (18) would suggest either no change, or a slight improvement, in some pulmonary function measures following exercise in nonpolluted conditions. We found a most dramatic decrease in vital capacity and maximum expiratory flow which occurred immediately after exercise regardless of when the exercise period occurred. Subsequent to the exercise, there was either an improvement or no further impairment of pulmonary function. This response presumably reflects the fact that the subject was breathing at both a greater depth and rate (during the exercise, approximately 37 liters to approximately 8 liters during quiet sitting). Thus the irritant gas was transported farther down the bronchial tree and was delivered in greater quantity (24) to the subject due to the increased ventilatory exchange. FEF 75%, which is thought to reflect small airways caliber (4), was reduced significantly only following exercise. Others (20) have found changes in FEF 75% and in slope of phase III only when subjects were exposed to high concentrations of ozone (0.75 ppm) in combination with exercise. An increase in mouth breathing could bypass the body's main ozone scrubber, the nose (24), and thus allow ozone to penetrate to the smaller peripheral airways. Once exercise is terminated, the peripheral airways are presumably no longer exposed to the same quantity of ozone and are thus able to recover. This may explain in part the minimal changes in pulmonary function in the subjects tested by Kerr et al. (17). They made their measurements almost 2 h after each of the two 15-min exercise periods. The total amount of work performed in their two exercise periods was similar in duration and intensity to the single period in this study and the total duration of their exposure periods was 6 h in contrast to our 2-h exposures. However, their nonsmokers showed few of the changes seen in our subjects. In failing to measure pulmonary function following exercise, they may have missed important changes due to ozone.

It is of some practical interest that the decrease of vital capacity was greater when ozone and heat exposure were combined since heat and air pollution episodes often coincide. At least some of this effect must be attributed to the increased ventilation and thus volume of ozone inspired which occurred during the heat exposures. The lack of a significant effect of heat exposure on any flow-related variables suggests that some mechanism other than bronchoconstriction is probably involved.

These findings are of considerable importance in the design of any experiment in which exercise is used as a method to increase exposure to pollutants. One should consider the length of time after the end of the exercise period as any decrements in pulmonary function which result from pollutant exposure may begin to show improvement before the subject leaves the polluted atmosphere.

Exposure to a high concentration of ozone (0.75 ppm) in combination with intermittent exercise has been shown to result in an 11% reduction in maximum work performance (9). Performance in cross-country running has also been inversely correlated with oxidant levels (22). However, these performance decrements may be at least partially related to motivation or discomfort rather than cardiorespiratory impairment. As we have shown, even light activity in an ozone environment can produce temporary impairment of lung function. The effects of regular outdoor activity in a polluted environment are in need of further investigation.

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